The X-target: a high-gain and robust target design for HIF

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Presented at
19th International Symposium on Heavy Ion Inertial Fusion
August13, 2012

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CH11231

Outline

- X-Target rationale and architecture
- Implosion and fuel assembly
- Ignition and burn propagation
- Proof of principle design / Further studies
- Interface Instabilities
- Conclusions

THE X-TARGET

In search of a simpler and more robust type of heavy ion target for IFE

A target that could be illuminated from one side with a beam array at small angles near a polar axis to facilitate thick-liquid protected chamber designs

Simple fabrication with extruded DT fill, robust RT and mix stability with very small fuel convergence ratios (~ 5 to 7)

The compressed fuel should be able to be ignited with a beam of similar characteristics as the one used for compression

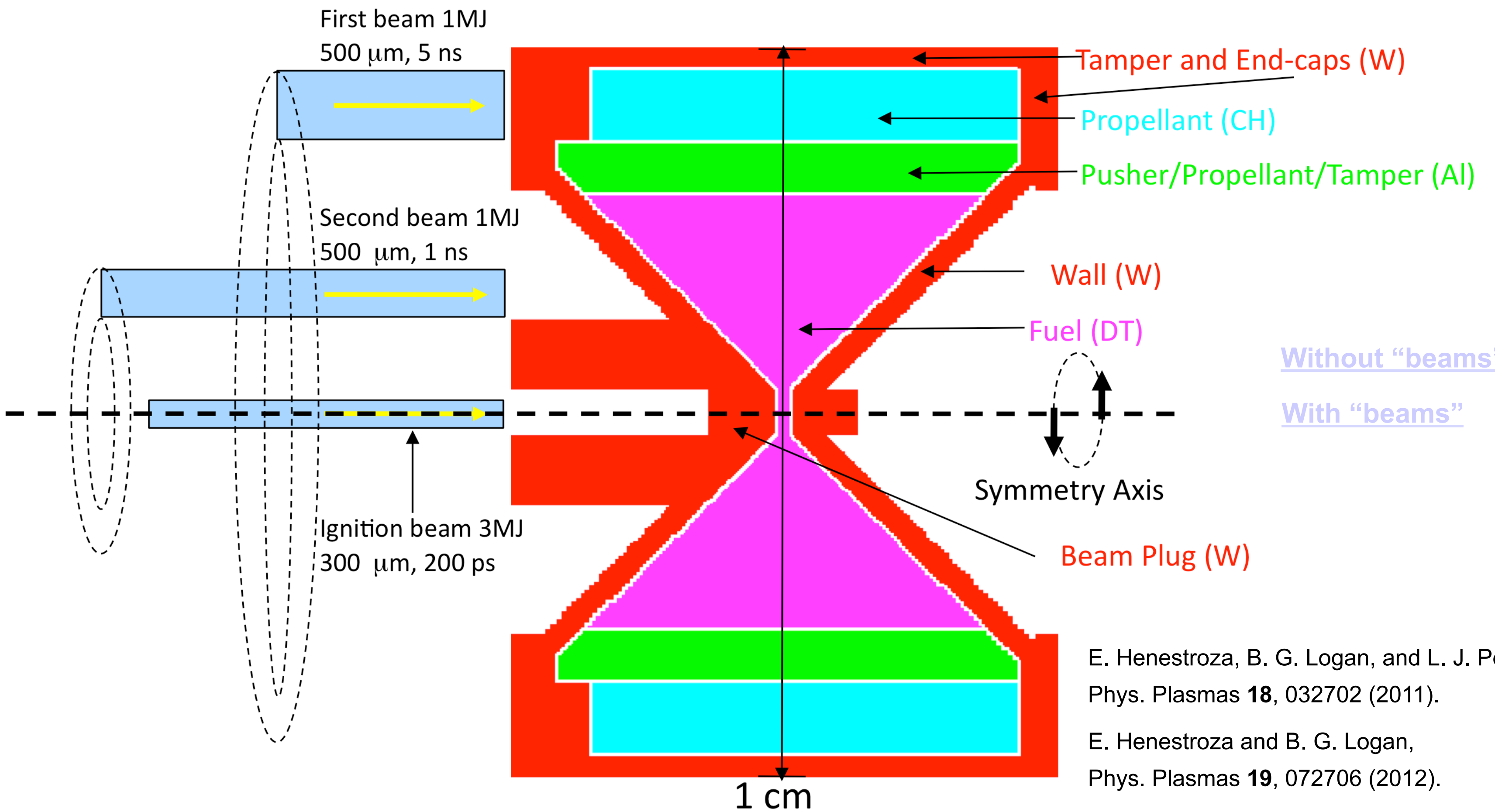
There is a long history of heavy-ion beam driven fast ignition and related fuel assembly (Mashke, Tabak, Callahan, Bangerter,…)

- 1-D and 2-D studies of solid and hollow ion beam ignition of preformed fuel assemblies down to 100 g/cm^3 (Herrmann, Tabak, Atzeni)
- Studies of heavy ion fast ignition and fuel assembly using single 100 GeV ion beams at ITEP (Russia)

The X-Target-Mark2: XMK2

20 GeV Rubidium beams (1.0+1.0+3.0 = 5.0 MJ)
Yield = 1.5 GJ

1st, 2nd, and ignition beams are many beams with overlapping spots modeled as annuli



Without "beams"

With "beams"

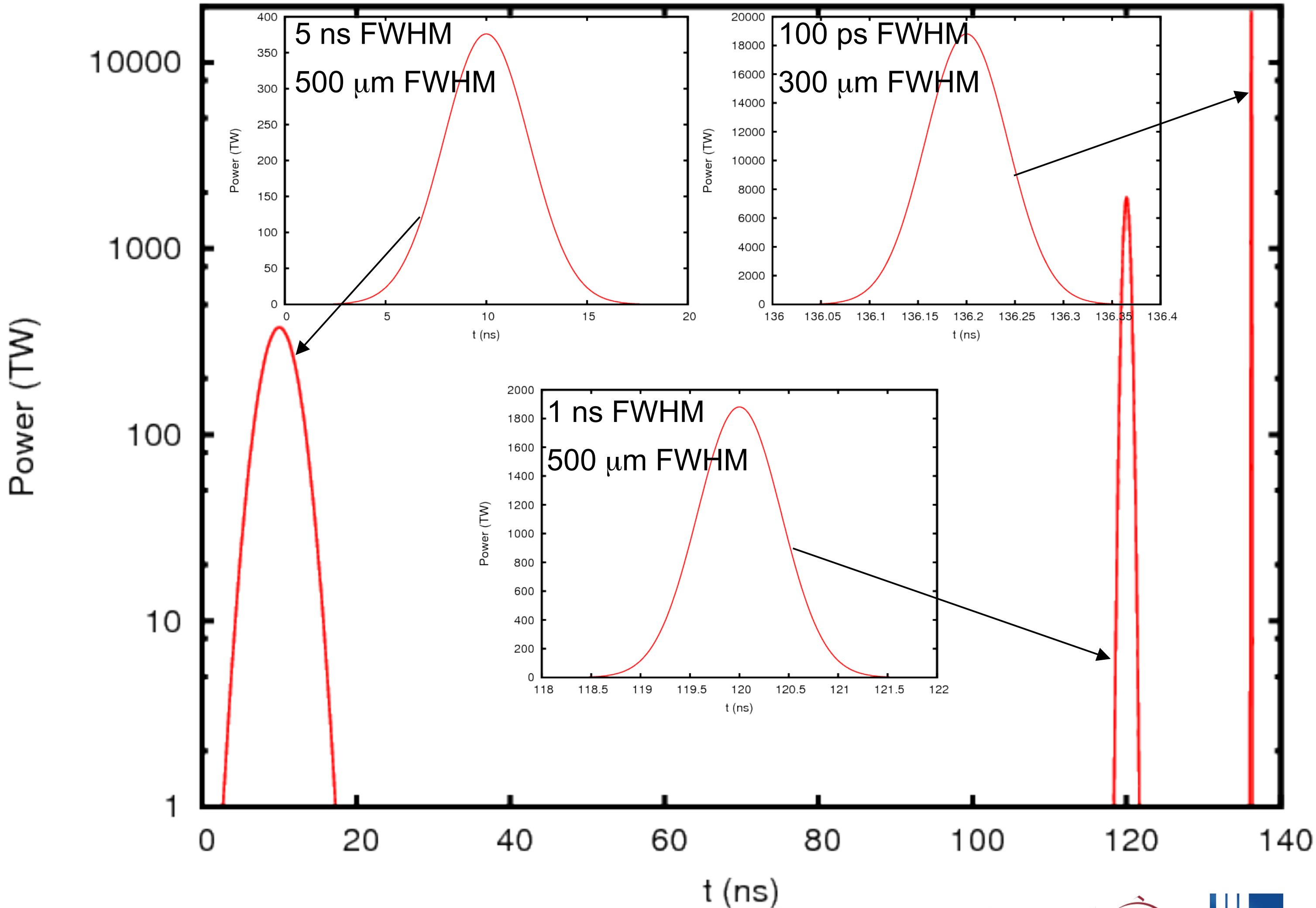
E. Henestroza, B. G. Logan, and L. J. Perkins, Phys. Plasmas **18**, 032702 (2011).

E. Henestroza and B. G. Logan, Phys. Plasmas **19**, 072706 (2012).

Beam-power gaussian time-profiles of XMK2

20 GeV Rubidium beams (1.0+1.0+3.0 = 5.0 MJ)
Yield = 1.5 GJ

All transverse beam profiles are also gaussian



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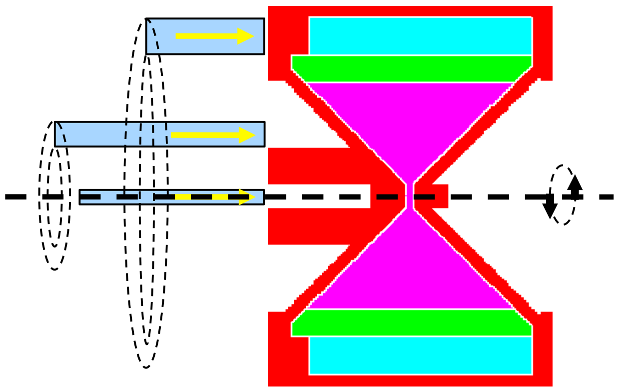
2-D implosion simulations of the X-target using HYDRA

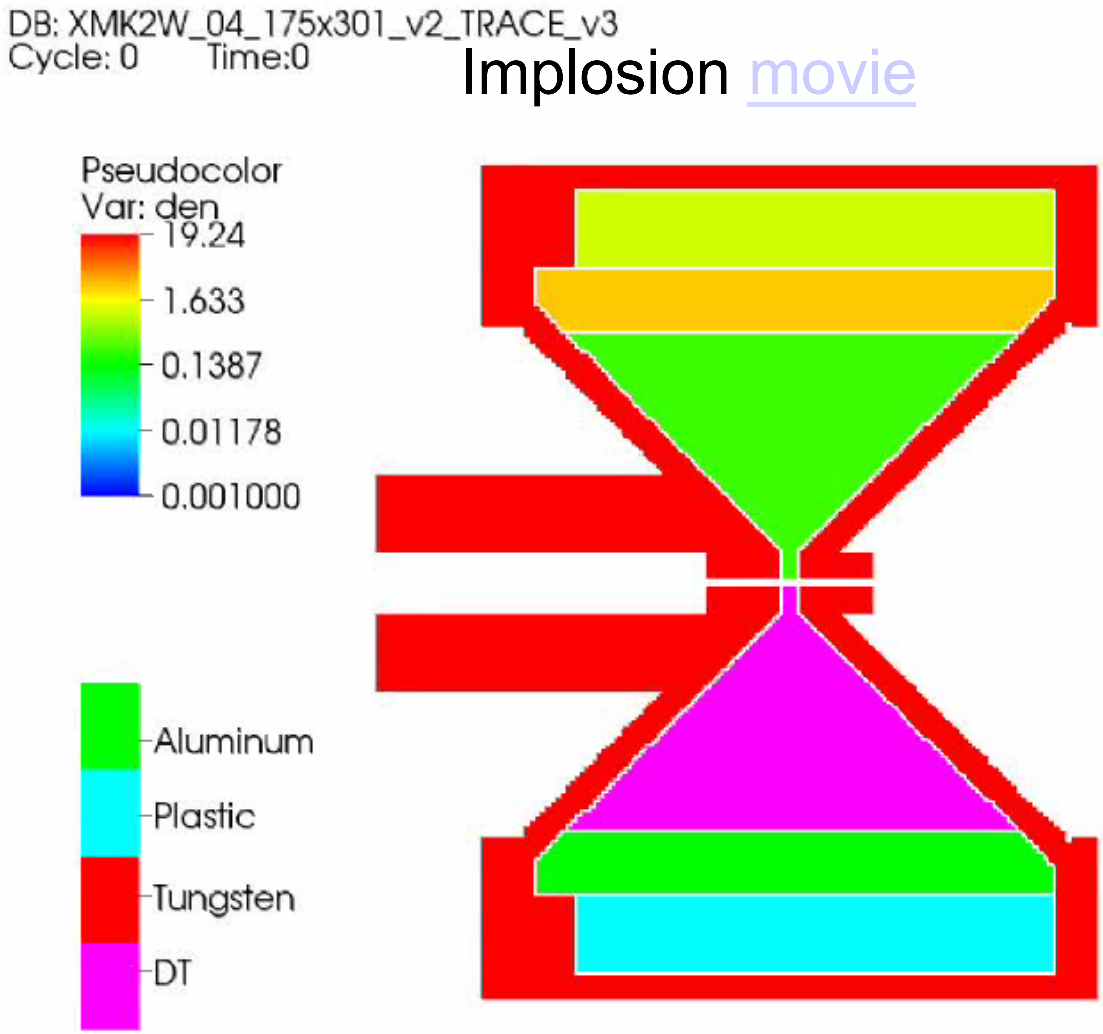
- **Hexahedral Eulerian mesh for a 1 degree sector about the azimuth (2D-RZ runs)**
- **LEOS EOS and Online Opacity tables**
- **Radiation diffusion or IMC with 50 groups**
- **Ion beam ray tracing package**
- **Thermonuclear burn**



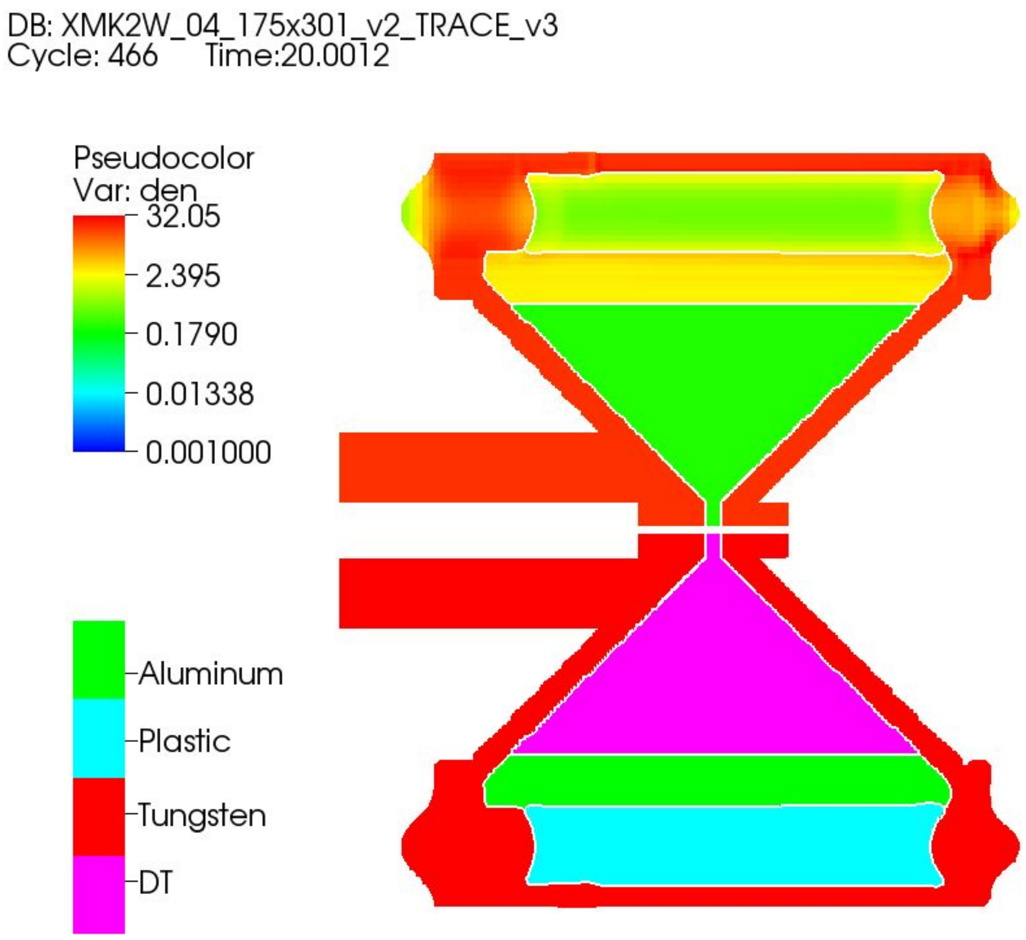
We found that:

- **The axially directed heavy ion beams can compress the DT fuel radially, with quasi-3D spherical convergence**
- **The beam-heated tamper expansion can favorably affect the implosion symmetry, as the pressure in the tamper much exceeds that in the beam heated DT regions**
- **Beam deposition that explodes the entrance tamper window is approximately balanced by an equal deposition in the far end of the beam channel, thus resulting in a nearly P1-symmetric implosion**
- **Tamper motion elsewhere is minimal, and no evidence of high RT mix is seen**
- **Radiation is not an important factor to calculate the compression of the fuel**
- **Radiation is more important to properly calculate the burn propagation**

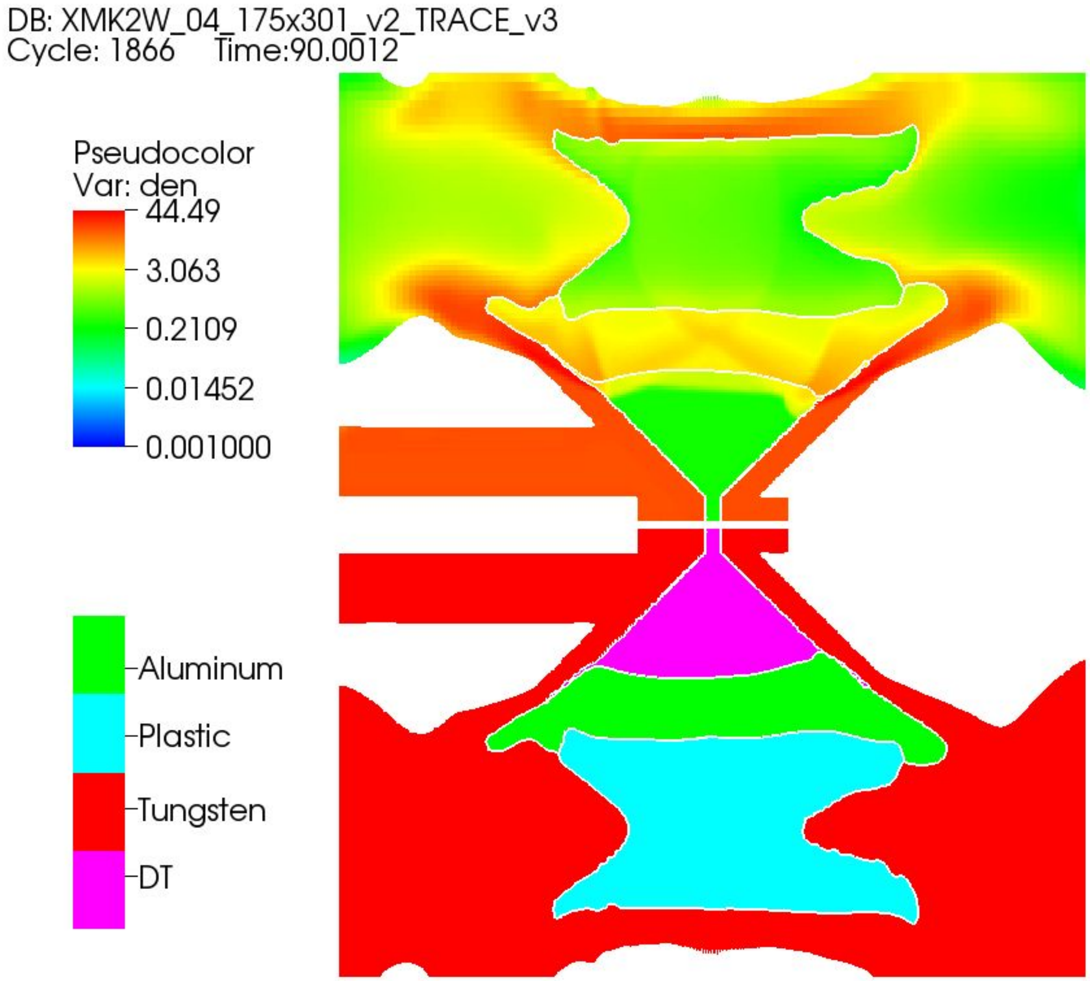
Implosion movie



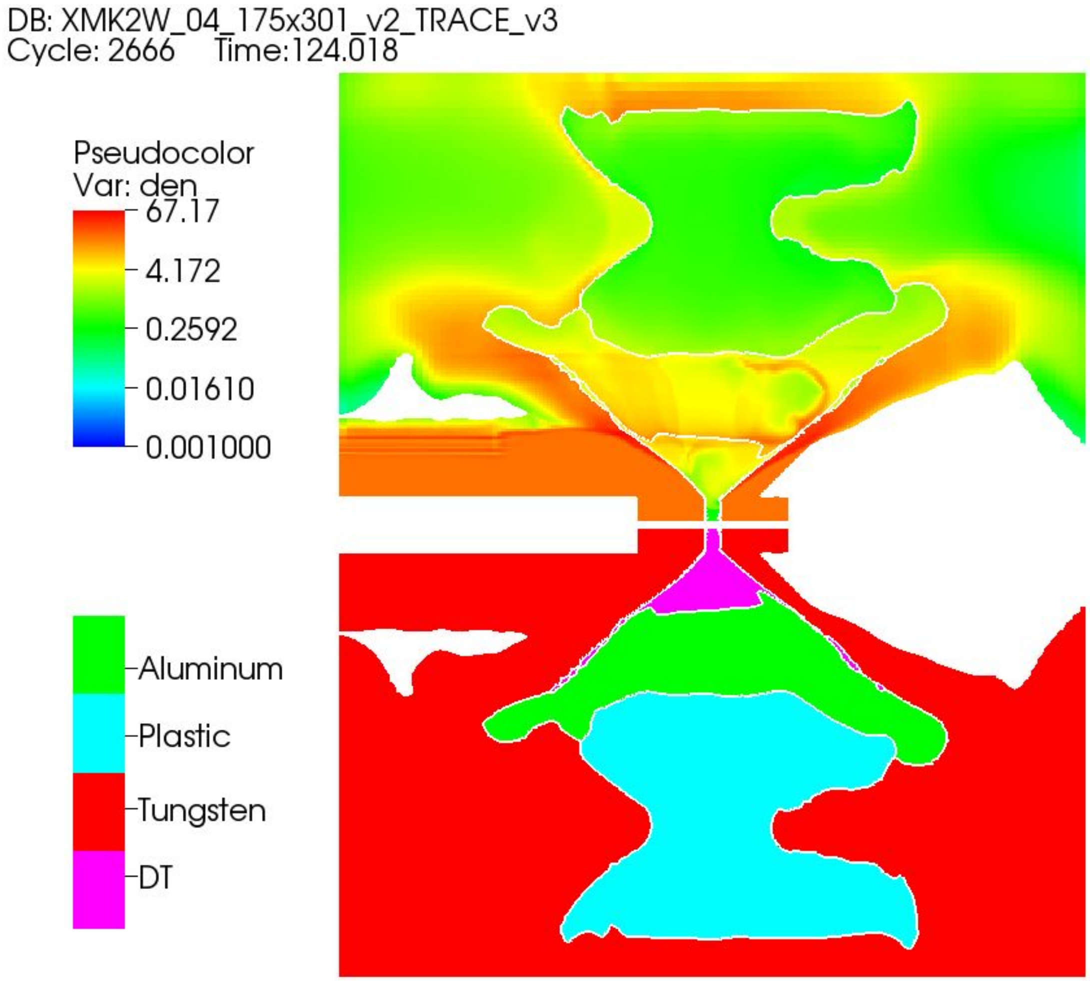
First beam explodes the end-caps and propellant



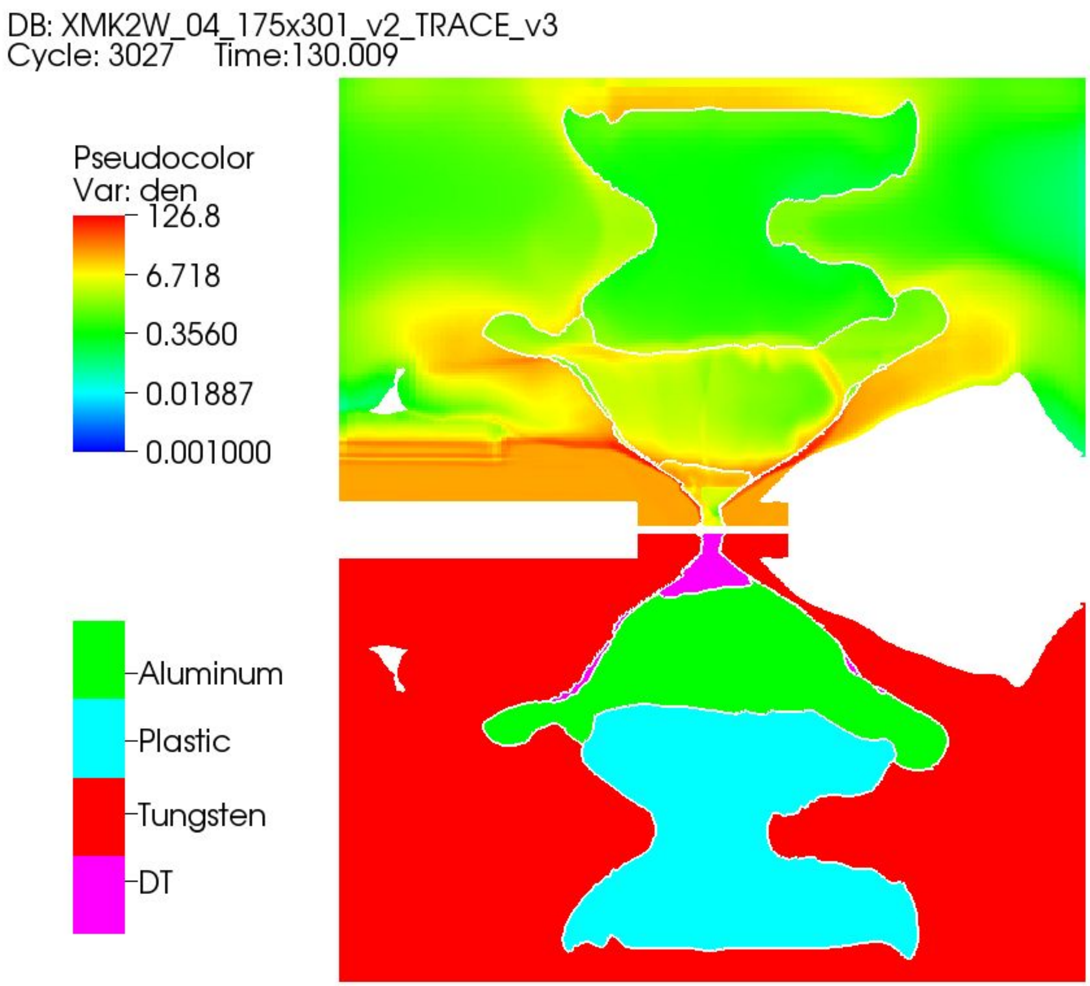
Pusher compressing the fuel



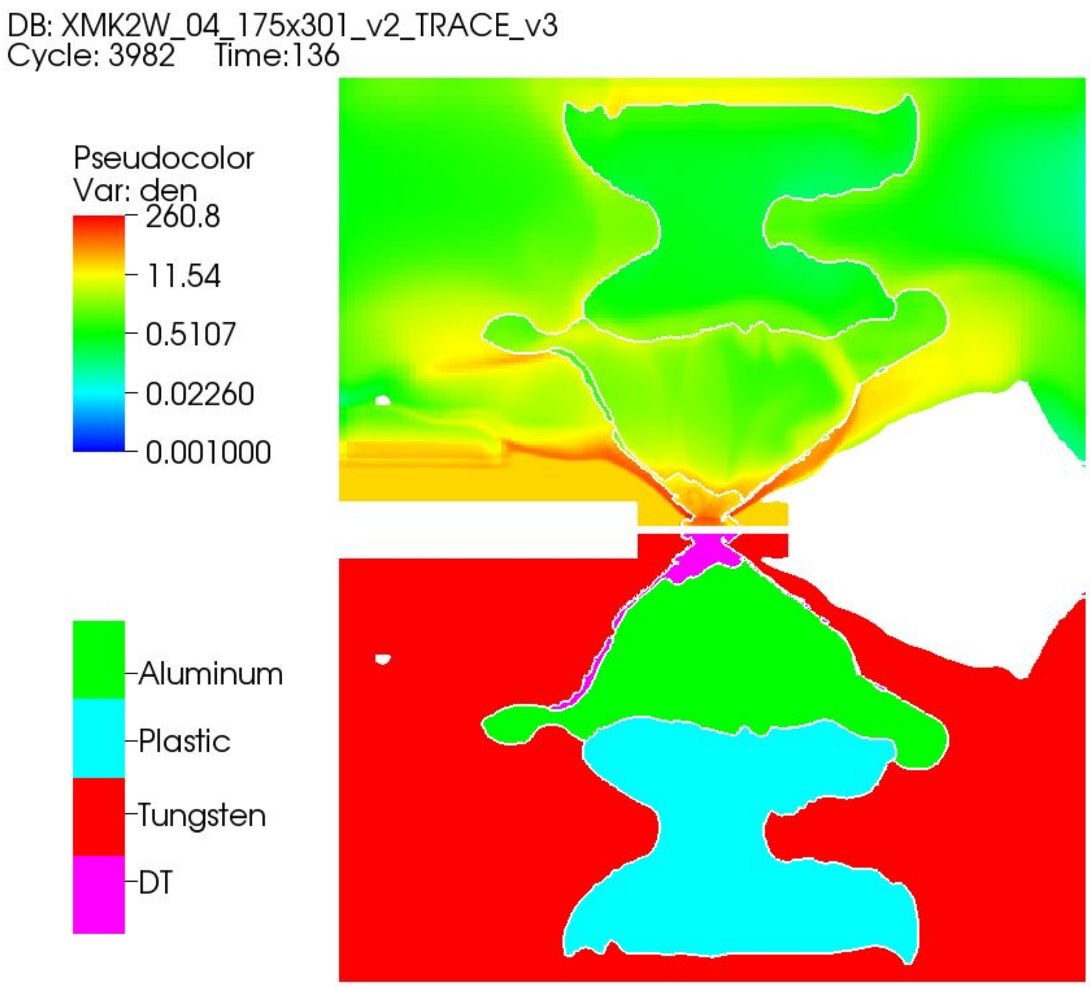
Second beam explodes the pusher



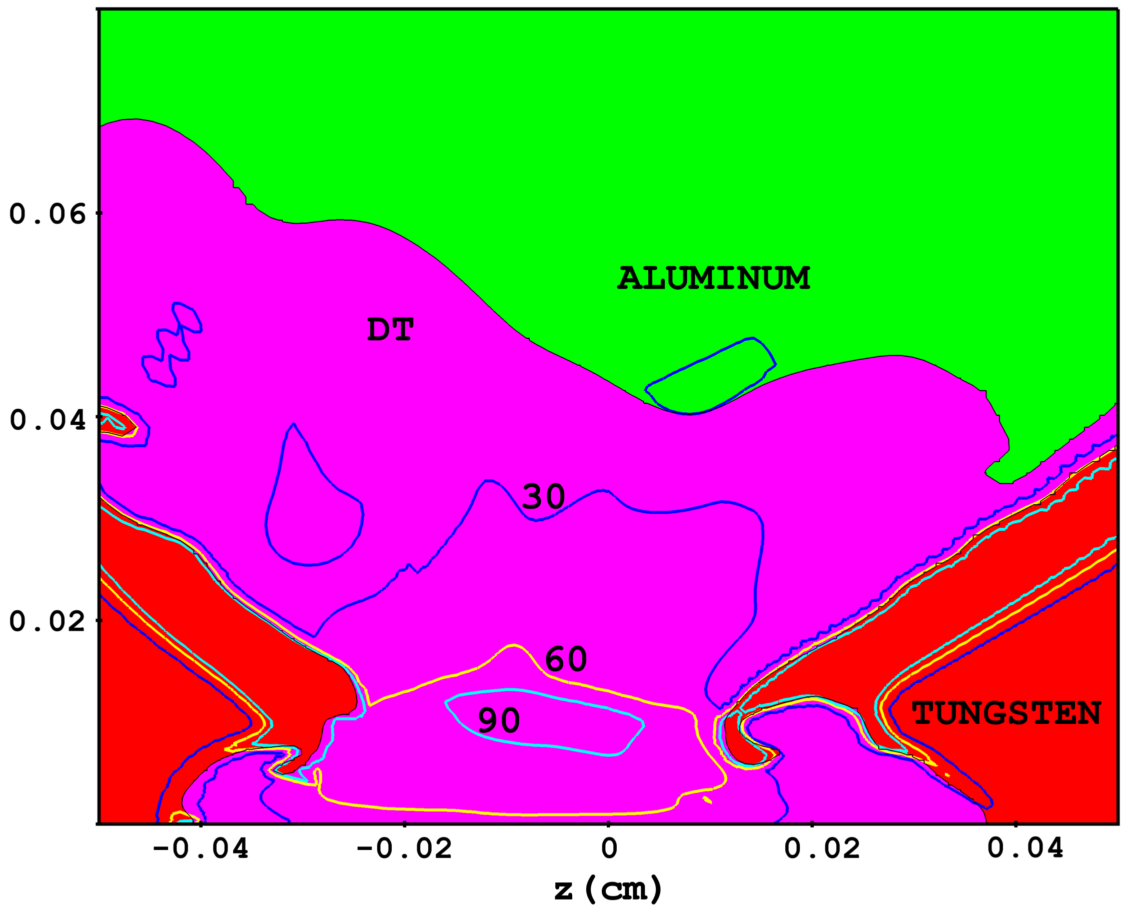
Exploded pusher keeps compressing the fuel



Time of “maximum” compression



Material distribution and density contours at time of "maximum" compression



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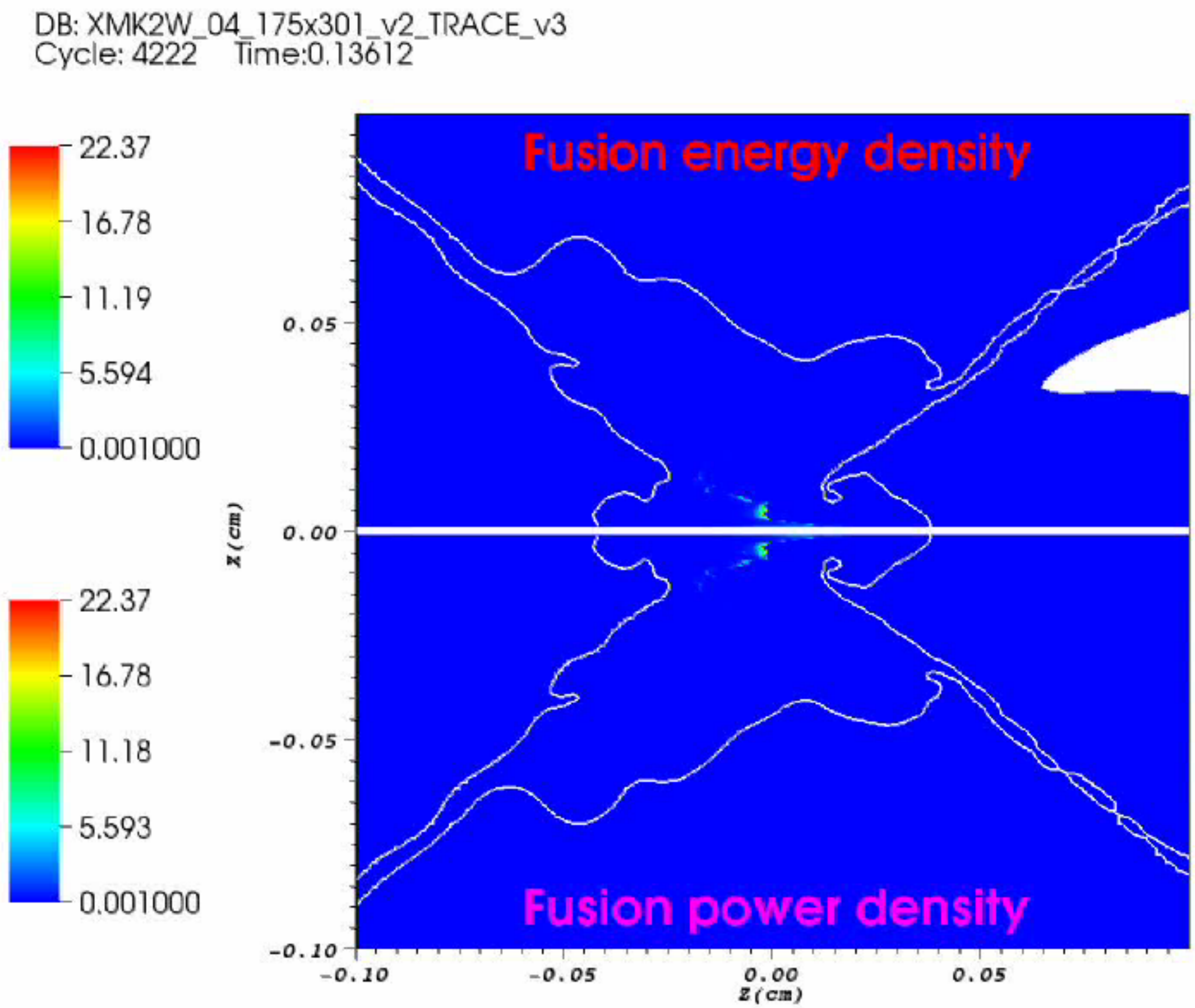
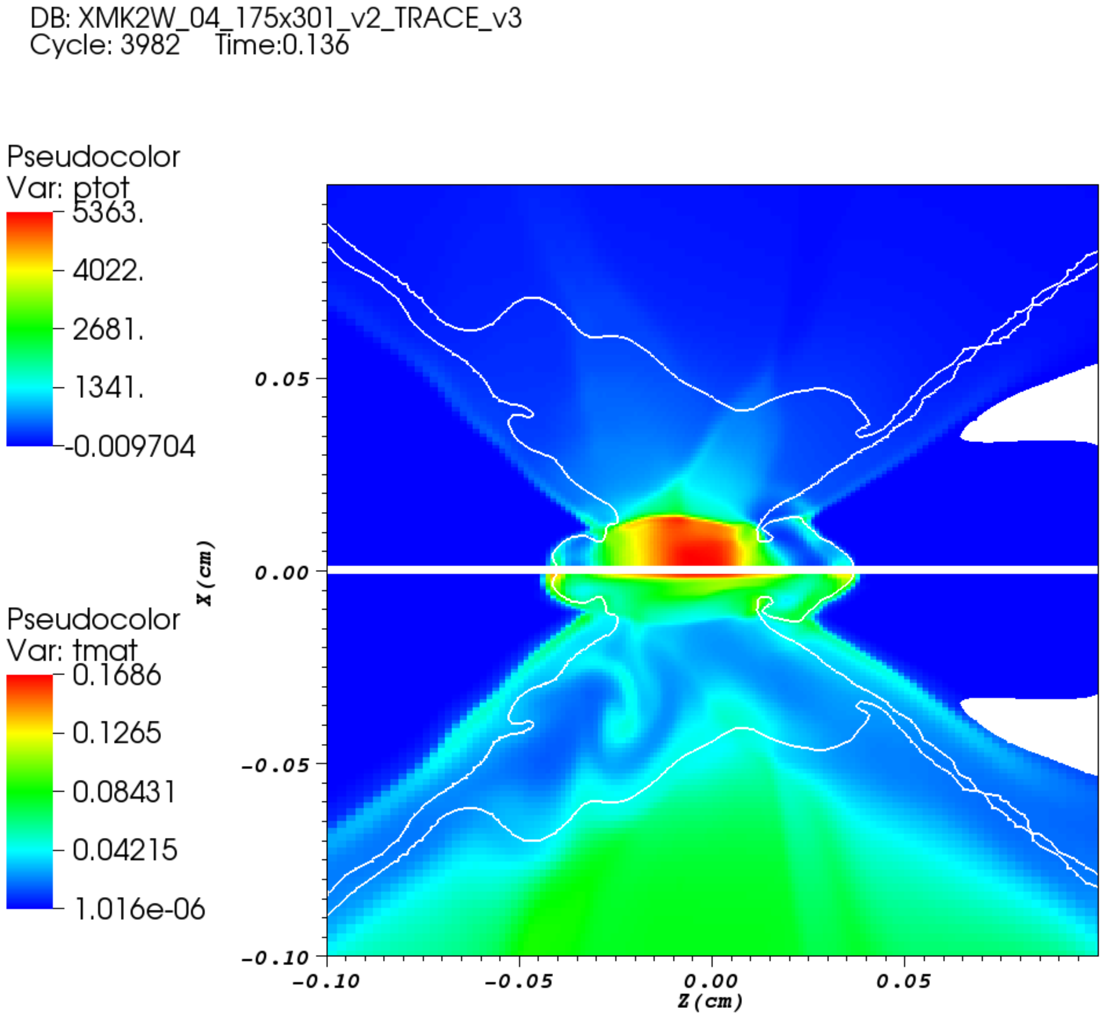
From M. Marinak et al.

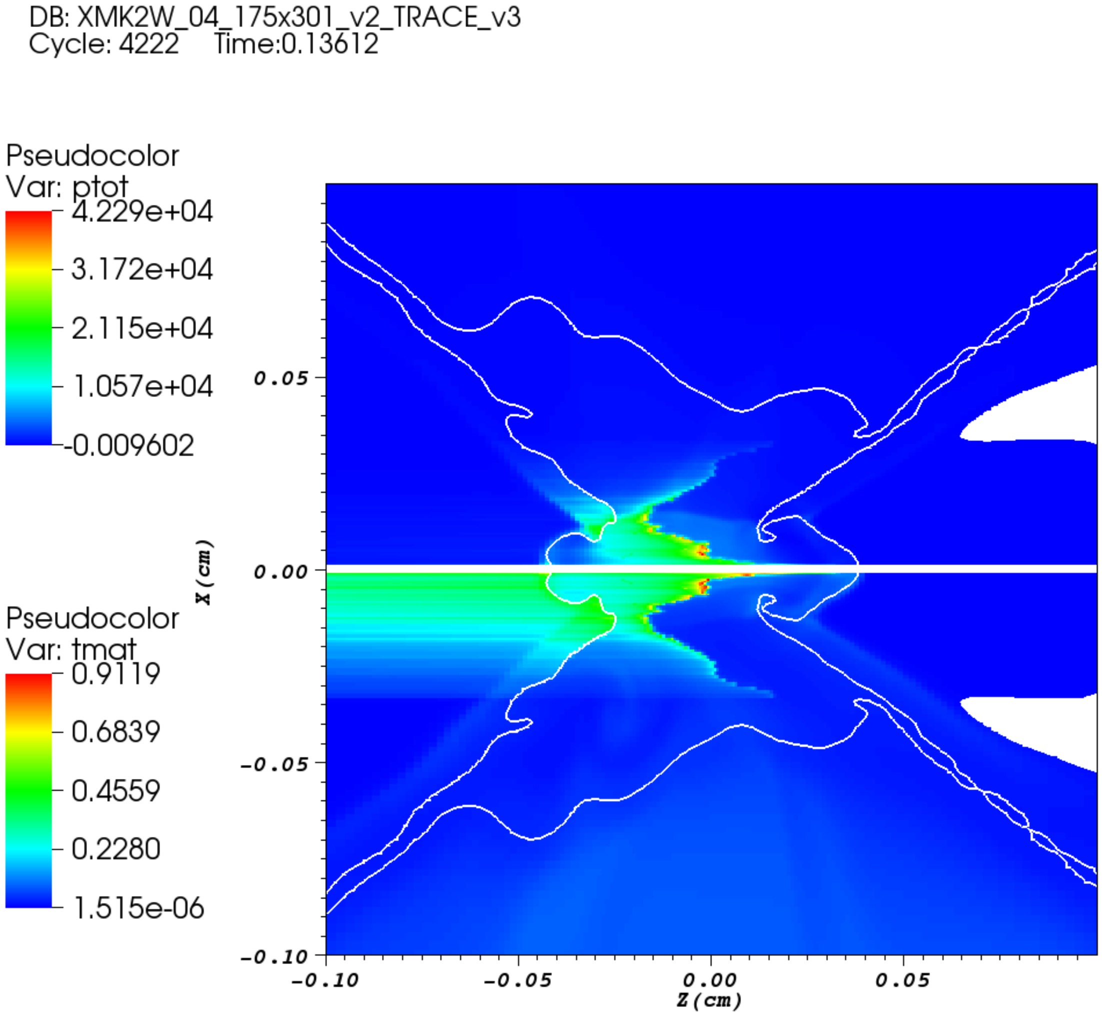
Cumulative thermonuclear energy per unit volume



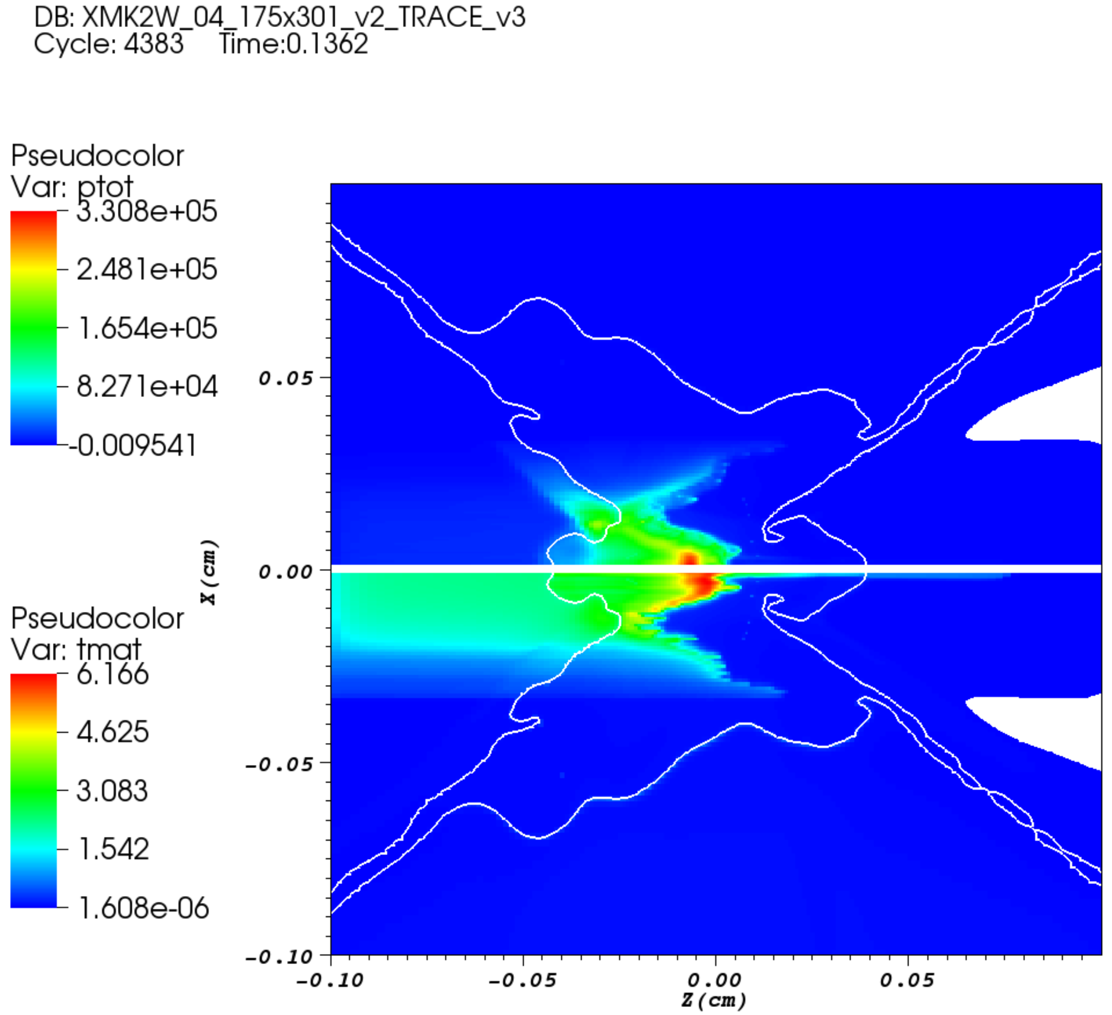
Density at time of "maximum" compression (linear scale)



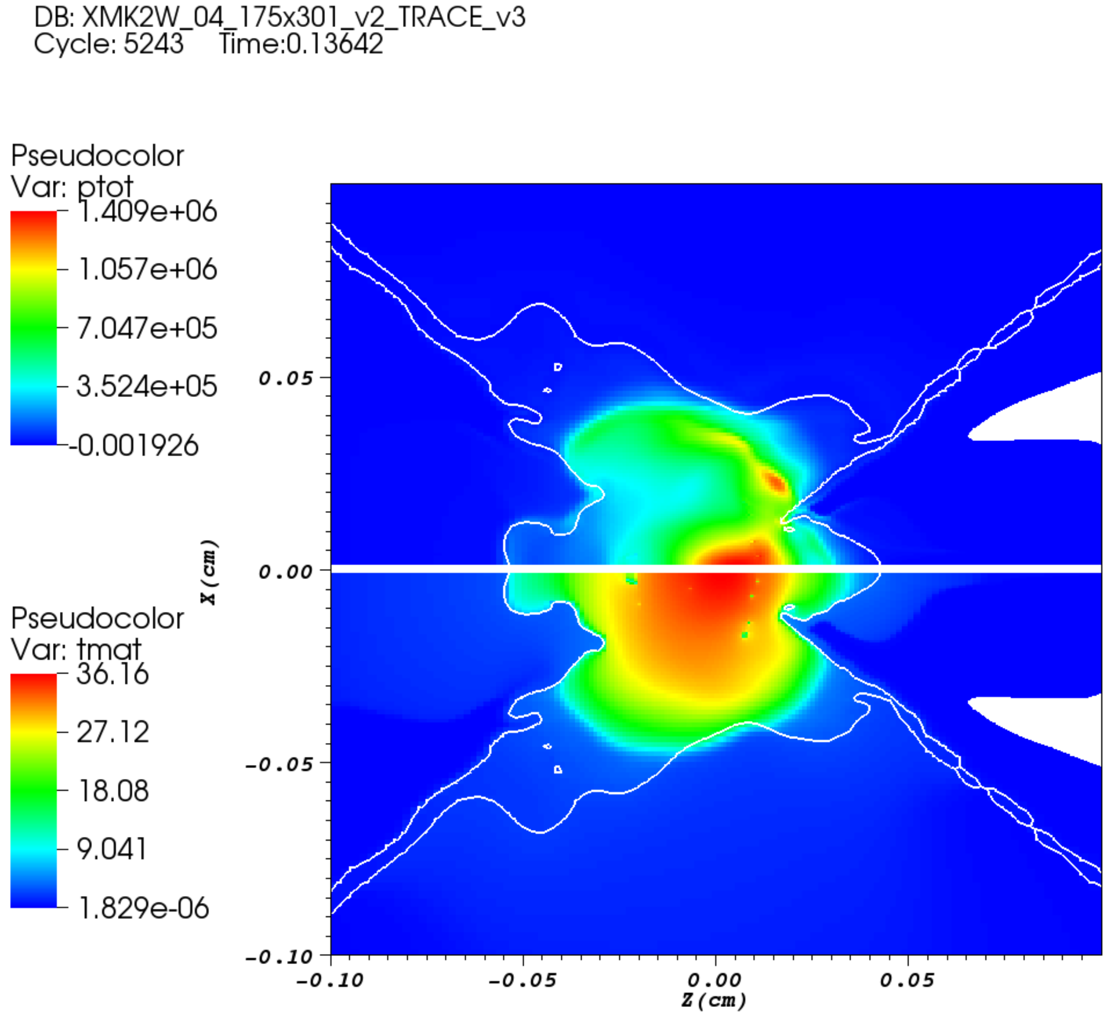
Pressure and temperature 80 ps before ignition-beam peak power



Pressure and temperature at ignition-beam peak power



Pressure and temperature at peak fusion power



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Proof of Principle Design gets 300X gain

- The proof of principle design uses two 1MJ, 20 GeV Rubidium beams for compression, pulse lengths of several ns, and annular thickness of about 1 mm
- Other ions with equivalent range as the 20 GeV Rb may be used, e.g., 90 GeV U
- Our initial simulations have achieved a compression ratio of ~400, from an initial DT density of 0.25 g/cm^3 to a final density of about 100 g/cm^3 and confinement parameter ρR of about 2 g/cm^2

- At full compression, a third "ignition" annular or solid beam is injected through a 600 μm diameter channel
- This fast ignitor beam is also a 20 GeV Rb beam with an energy of 3 MJ and a pulse length of 100 ps (FWHM), and annular thickness of about 600 μm
- The ignition-beam-pipe plug near the vertex of the X-target is adjusted to place the Bragg peak near the location of maximum ρR.

- The X-Target requires a total beam energy of (1+1+3) 5 MJ and produces a yield of 1.5 GJ

This design has not been optimized and still represents work in progress

THE X-TARGET
Further studies

LONG TERM

- **Target fabrication errors, beam aiming errors and non-axisymmetric annular beams**
- **Preheat of DT fuel by beam halo and beam prepulse**
- **Beam-target interaction/Ion deposition profile**
- **Beam dynamics issues (longitudinal and transverse compression)**
- **Integrated design**
- **Interface instabilities**

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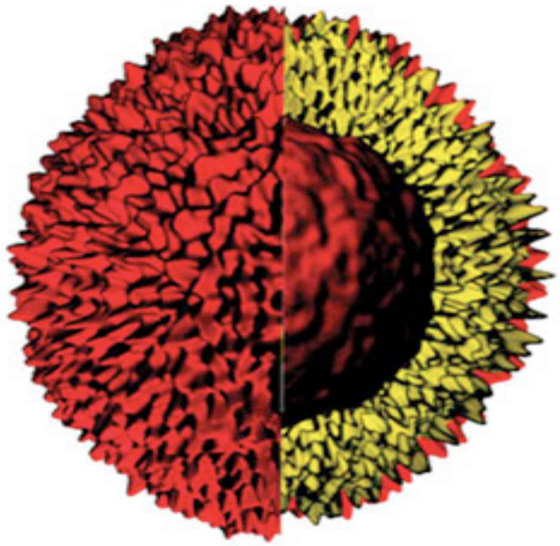
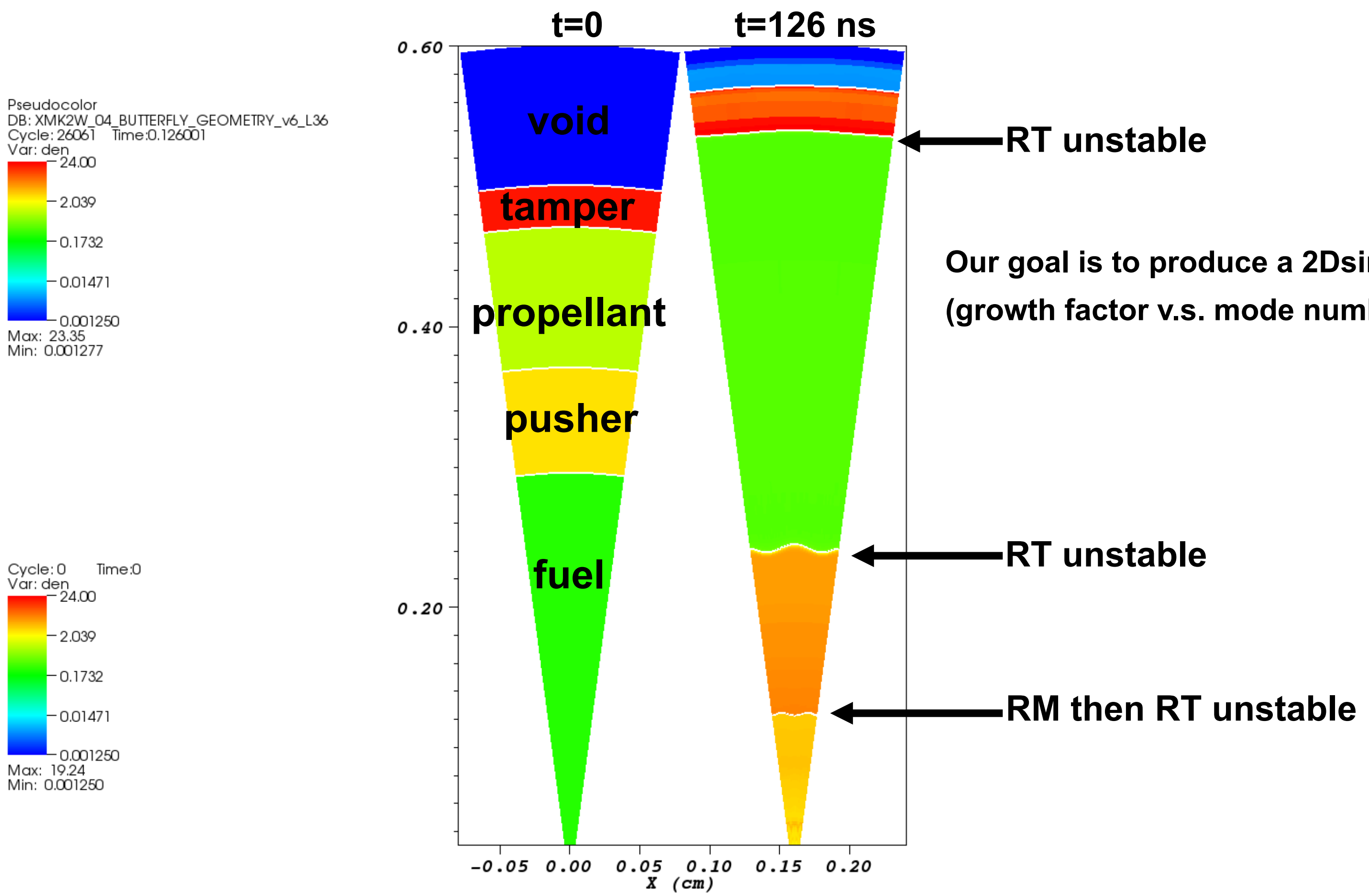


From M. Marinak et al.

Rayleigh-Taylor and Richtmyer–Meshkov 2D single-mode stability studies using a 15 degrees polar wedge of a sphere that mimics the implosion dynamics of the X-target



Our goal is to produce a 2Dsingle mode stability plot (growth factor v.s. mode number)

movie

RM growth at the fuel-pusher (DT-Al) interface in a 15 degrees polar wedge and Legendre modes L=36,72,108,144,180,216

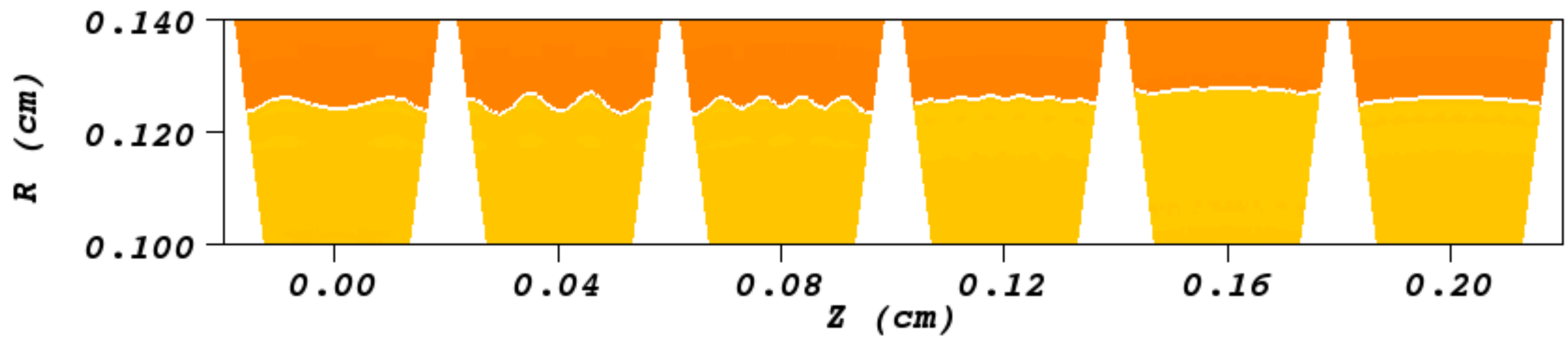
Initial perturbation is 1 μm amplitude

Growth factors < 50

From start of implosion to time of injection of second beam

Movie

L=36 L=72 L108 L=144 L=180 L=216



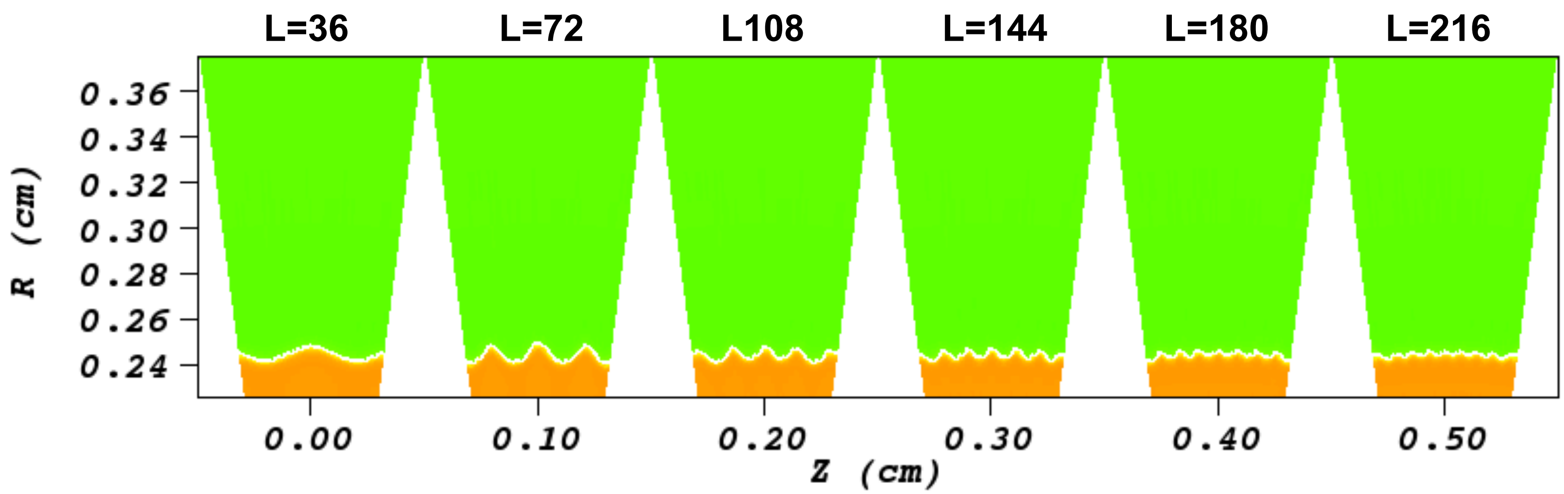
RT growth at the propellant-pusher (CH-Al) interface in a 15 degrees polar wedge and Legendre modes L=36,72,108,144,180,216

Initial perturbation is 1 μm amplitude

Growth factors < 100

From start of implosion to time of injection of second beam

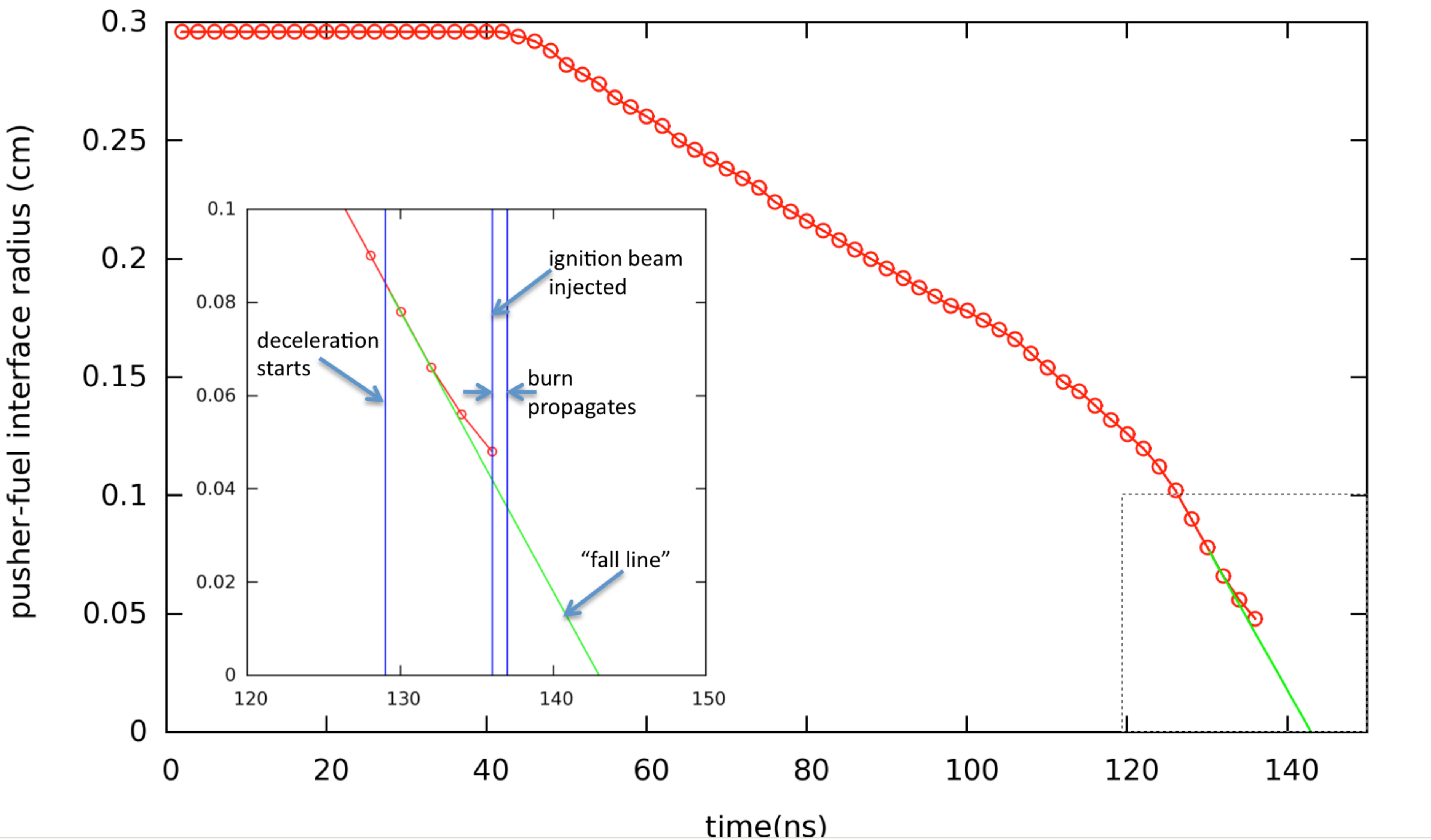
Movie



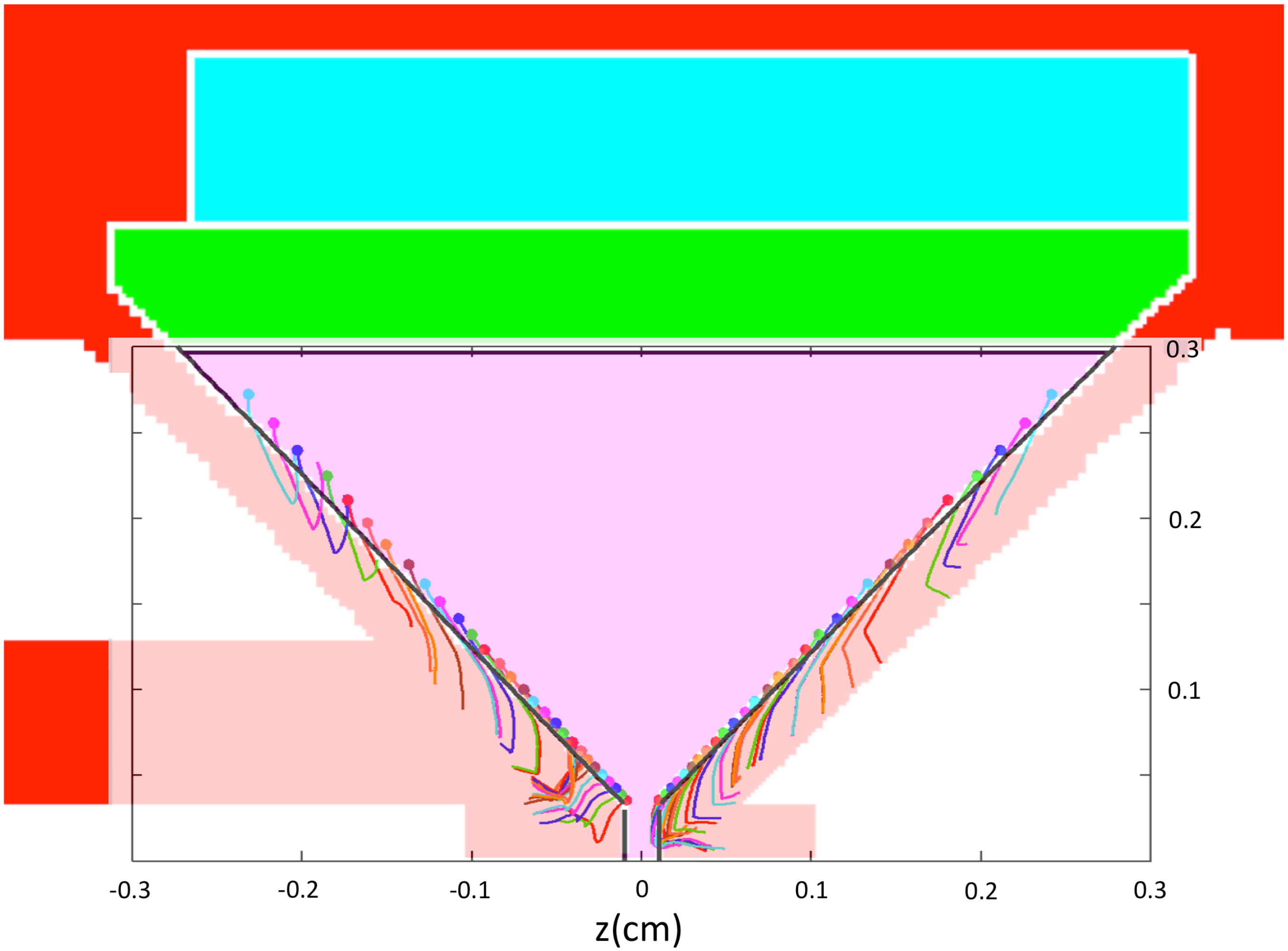
Estimate of RT growth at the DT-Al interface during deceleration

- The deceleration phase starts at 128 ns and lasts for 8 ns, at which time the ignition beam is injected
- An upper bound for the deceleration (at 132 ns) is a ~ 3.6e14 cm/s^2 at a radius of 0.0600 cm and speed v~ 6e6 cm/s for a free fall time of 10 ns.
- Since the Atwood number is also almost constant and equal to 0.25, the e-folding time for perturbations of wavenumber k is ~ 1e-7/sqrt(k) with k in cm^{-1}
- For example, with perturbations of mode number L=36 at R=0.06 cm, we have k=600 cm^{-1}, which produces an e-folding time of ~ 4 ns. For perturbations of mode number L=216, we have k=3600 cm^{-1}, which produces an e-folding time of ~ 1.7 ns
- The penetration depth of the instability arising from random perturbations can be estimated from h~factor*AtwoodNumber*deceleration*deceleration_time^2=factor*60 microns. Usually the factor is about 10%, resulting in an estimated penetration depth of 6 microns

Pusher-fuel-interface trajectory. The inset shows the relevant timings of the implosion and fuel burn dynamics



Kelvin–Helmholtz instability:
Tracing fluid elements along wall during implosion do not show particles convecting to the ignition region



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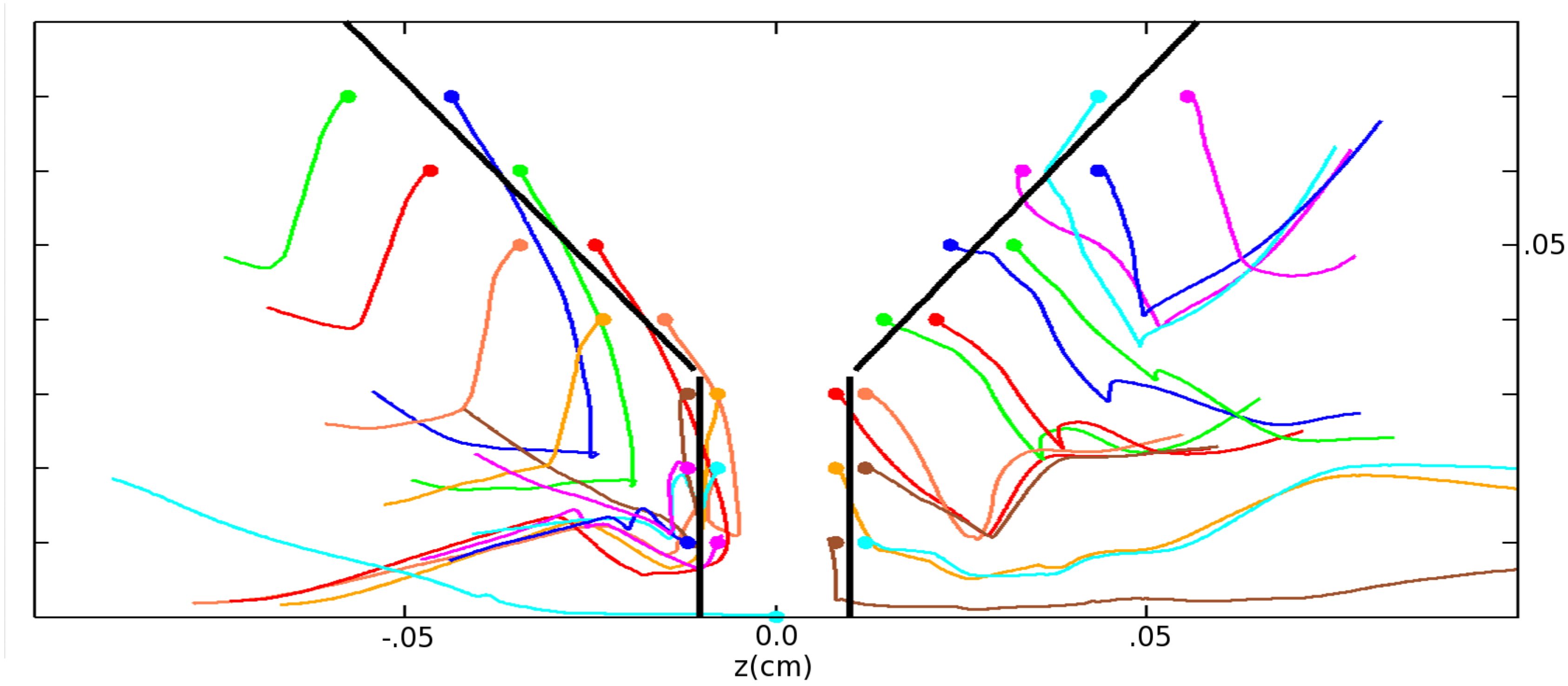

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- **The X-target offers potentially high gains > 200 with high yields sufficient for simple liquid concepts such as HYLIFE, and can mitigate concerns about the cost of targets.**
- **Light metal (e.g. Al) pushers can enhance quasi-spherical DT compression to higher peak DT density and rho-r with negligible DT-Al interface mix, but increases metal mix from the X-side walls.**
- **The key to higher gains from quasi-spherical DT compression in Xtargets (relative to heavy ion cylindrically-driven implosions) brings inherent risk of heavy metal mix observed from the side cones.**
- **Depending on initial X-vertex-case geometry, reducing grid spacing to a few microns in parallelized HYDRA runs, shows total metal mix within the ignition zone saturating to levels that diminish, but do not preclude, high X-target gains >>100.**
- **Near term work has focused on hydro-stability (mix due to RT and KH); more work on mitigating mix is planned.**
- **Much optimization of the X-target remains to be done, with the potential to achieve target gains above 1000.**
- **The very high ion kinetic energies and gains accepted by the X-target motivates the consideration of high gradient RF linacs (can allow lower efficiency) as well as induction linacs as drivers. More study of accelerator options for the X-target is needed.**
- **There are a number of side-wall mix mitigating strategies that have yet to be investigated, and we invite other researchers to join the fun in exploring how much higher X-target gains in 2 and 3 D might be optimized towards the 1-D potential gain of 1000**